**Author(s):** Izotov, I.; Kalvas, Taneli; Koivisto, Hannu; Komppula, Jani; Kronholm, Risto; Laulainen, Janne; Mansfeld, D.; Skalyga, V.; Tarvainen, Olli

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# Cyclotron instability in the afterglow mode of minimum-B ECRIS

I. Izotov,[1,a)] T. Kalvas,[2] H. Koivisto,[2] J. Komppula,[2] R. Kronholm,[2] J. Laulainen,[2]
D. Mansfeld,[1] V. Skalyga,[1,3] and O. Tarvainen[2]
[1]*Institute of Applied Physics, Russian Academy of Sciences (IAP RAS), 46 Ul'yanova St., 603950 Nizhny Novgorod, Russia*
[2]*Department of Physics, University of Jyvaskyla, P.O. Box 35 (YFL), 40500 Jyvaskyla, Finland*
[3]*Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina St., 603950 Nizhny Novgorod, Russia*

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It was shown recently that cyclotron instability in non-equilibrium plasma of a minimum-B electron cyclotron resonance ion source (ECRIS) causes perturbation of the extracted ion current and generation of strong bursts of bremsstrahlung emission, which limit the performance of the ion source. The present work is devoted to the dynamic regimes of plasma instability in ECRIS operated in pulsed mode. Instability develops in decaying plasma shortly after heating microwaves are switched off and manifests itself in the form of powerful pulses of electromagnetic emission associated with precipitation of high energy electrons. Time-resolved measurements of microwave emission bursts are presented. It was found that even in various gases (helium and oxygen were studied) and at different values of magnetic field and heating power, the dynamic spectra demonstrate common features: decreasing frequency within a single burst as well as from one burst to another. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4935624]

## I. INTRODUCTION

A well-known specific feature of ECR heating is that the energy of the microwave source is mostly embedded into transverse momentum of the electrons, thereby forming positive gradient in the electron velocity distribution function (EVDF). Resonant interaction between energetic strongly anisotropic electrons and the plasma electromagnetic waves makes the plasma prone to kinetic instabilities resulting in a generation of powerful electromagnetic radiation and bursts of energetic electrons leaving the magnetic trap. Studies of cyclotron instabilities in magnetized plasmas have a long history but still remain topical, as the cyclotron instability is an important loss channel of the electron energy.[1] For example, in modern ECR sources of multiply charged ions, which are widely used as injectors of heavy ions for accelerators, the precipitation of particles due to instabilities modifies the energy distribution function of hot electrons and charge state distribution of the ions, thus limiting the average charge state of extracted ion beams.[2] This paper is devoted to the study of the dynamic regimes of cyclotron instabilities in non-equilibrium plasma of a minimum-B electron cyclotron resonance ion source (ECRIS) operated in pulsed mode. The production of intense ion beams in so-called "afterglow" mode is of great interest since it allows achieving ion currents substantially higher than currents during continuous (cw) operation.[3,4] The afterglow occurs when the microwave generator is switched off and the plasma begins to decay. The lifetime of cold electrons is much shorter than the lifetime of relativistic hot electrons that are well-confined by the magnetic field. Thus, the anisotropy of the EVDF increases during the afterglow transient. The energy stored mostly by hot electrons[5] is rapidly released in the form of particle losses and electromagnetic radiation in optical, microwave, and x-ray bands. The observed oscillations of extracted ion current during the plasma decay were recently associated with a cyclotron instability driven by the resonant interaction of plasma waves with hot electrons with anisotropic velocity distribution.[6] In this article, we study the fine structure of the electromagnetic emission bursts related to cyclotron instability in decaying ECR plasma confined in a minimum-B magnetic field. First experimental data on the high-resolution dynamic spectra of five different types of kinetic instabilities in ECR discharge plasma were recently reported in Ref. 7.

## II. EXPERIMENTAL SETUP

The experimental data were taken with the room-temperature A-ECR-U type JYFL 14 GHz ECRIS.[8] The plasma was heated by a klystron amplifier at the frequency of 14 GHz. The klystron was operated in a pulsed mode by controlling the low-power input signal from an oscillator with a fast RF-switch with a rise/fall time of 40/100 ns. The magnetic field of the ion source is generated by two solenoid coils and a permanent magnet sextupole resulting to a so-called minimum-B field configuration. The ECR zone is a nearly ellipsoidal surface with constant magnetic field of $B_{ECR} = 0.5$ T. The magnetic field strength can be adjusted by varying the solenoid coil currents, which affects the injection and extraction mirror ratios as well as the $B_{min}/B_{ECR}$. The ion source was operated in the range of $0.68 < B_{min}/B_{ECR} < 0.80$.

A complete description of the magnetic field profile can be found from Ref. 9. Oxygen and helium plasmas in the

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[a)]Author to whom correspondence should be addressed. Electronic mail: izotov@ipfran.ru

 

pressure range of $4 \times 10^{-7} - 5 \times 10^{-7}$ mbar were studied. The electron cyclotron instabilities were detected with a bismuth germanate (BGO) scintillator coupled with a Na-doped CsI photomultiplier tube (PMT) with <4 $\mu$s resolution as described in previous work.[2] The detector is sensitive to bursts of bremsstrahlung, generated at the wall of the plasma chamber by energetic electrons, which are expelled from the magnetic trap as a result of the instability. Microwave emission of the plasma was measured through a WR-75 waveguide port incorporated into the injection iron plug. The emitted microwave signal was guided into Tektronix MSO 72504 DX oscilloscope through WR-75 waveguide, high-voltage break, waveguide-to-coaxial transition, power limiter, and tunable attenuator. The features of the oscilloscope—100 Gs/s sampling rate and 25 GHz bandwidth—allowed direct recording of the waveforms of electromagnetic field emitted by the plasma with temporal resolution of 20 ps. The frequency response of the WR-75 waveguide and waveguide-to-coaxial transition was measured to be flat in the range of 8-15 GHz. A schematic figure of the ECRIS and the experimental setup is shown in Fig. 1.

The investigations were performed in decaying plasma after switching off the klystron. The trailing edge of the TTL signal controlling the RF-switch was used to trigger the oscilloscope for high sampling rate acquisition of the microwave signal waveform.

## III. EXPERIMENTAL RESULTS

Figure 2 presents typical waveforms of the microwave electric field (upper curve) and bremsstrahlung (lower curve) signals recorded during the plasma decay. The data were taken in afterglow of a plasma discharge, initially sustained by 400 W of injected microwave power at $4.7 \times 10^{-7}$ mbar of oxygen and $B_{min}/B_{ECR} = 0.78$. The bremsstrahlung power flux signal, which is attributed to the precipitation of hot electrons from the trap, consists of a sequence of peaks lasting for some tens of $\mu$s. Despite the temporal resolution of the current-mode X-ray detector is not sufficient to detect variations of the bremsstrahlung signal at the level of 100 ns, the leading edge of each X-ray pulse is perfectly coincident with the microwave emission packets.

Figure 3 shows dynamic spectrograms of the microwave bursts, subsequently emitted during the plasma decay at 1.37 ms (Fig. 3, upper) and 6.3 ms (Fig. 3, lower) following the trailing edge of the 14 GHz microwave pulse. The signal was treated with Goertzel algorithm to build the spectral power density in each time domain in the range of 8-15 GHz with 10 MHz step (the spectral power density of the signal is indicated with false color). The horizontal line at 12.50 GHz is an artefact related to the sampling rate of the oscilloscope and subsequent analysis of the data. The first instability burst comprises a sequence of microwave packets and the frequency range of each wave packet is consistently lower in comparison to the preceding one. The dynamic spectrum of each pulse is typically descending in frequency, whereas the rate of frequency drift is increased with each

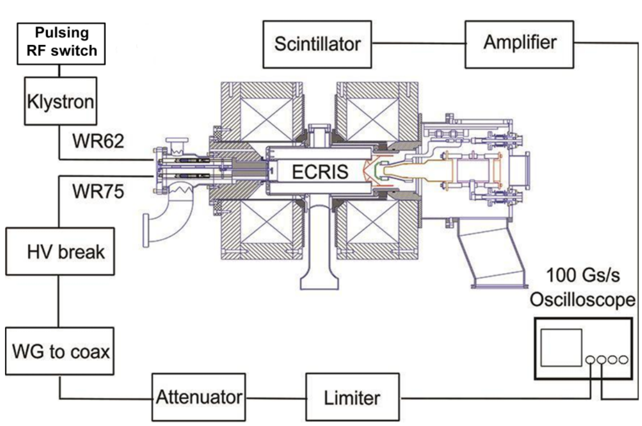


FIG. 1. Schematic figure of the experimental setup.

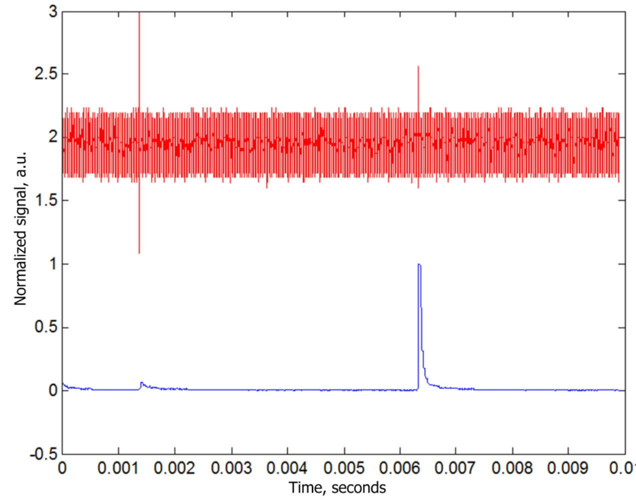


FIG. 2. Typical waveforms of the microwave electric field (upper curve) and bremsstrahlung (lower curve) signals during afterglow instability.

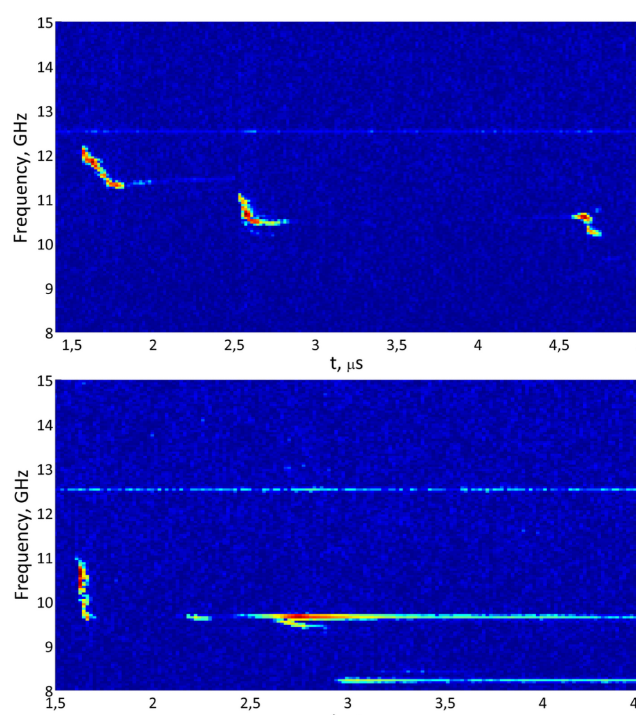


FIG. 3. Dynamic spectrograms of the microwave bursts at 1.37 ms (upper) and at 6.3 ms (lower).

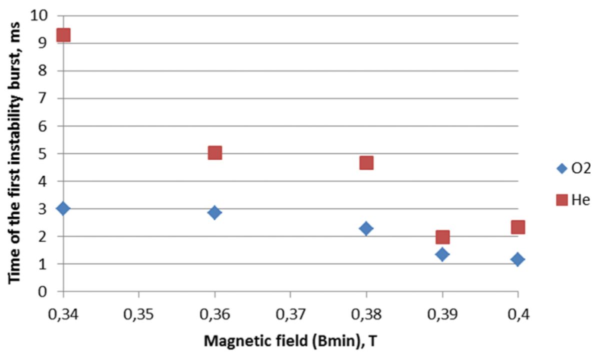


FIG. 4. Dependence of a delay between heating power trailing edge and the first instability burst on the magnetic field strength.

consecutive pulse. However, in some cases, the last pulse in the described sequence exhibits quasi-monochromatic narrow-banded harmonics shown in Figure 3 (lower). It was found that at different initial ion source settings (B-field strength, type of the gas, neutral gas pressure, and 14 GHz microwave power), the dynamic spectra demonstrate aforementioned common features: (i) decreasing frequency from burst to burst and (ii) falling tone during a single instability burst. The magnetic field strength significantly affect the delay between heating power trailing edge and the appearance of the first instability burst as well as the number of instability events during the afterglow. Figure 4 shows the dependence of the delay on magnetic field strength for oxygen and helium plasma at the same neutral pressure of $4.7 \times 10^{-7}$ mbar.

The delay decreases monotonically with increasing magnetic field strength, while the dependence on heating power shows threshold-like dynamics being rather insensitive to the power above 200 W. There are no significant distinctions between oxygen and helium plasma; although in helium plasma, the first instability pulse is observed much later.

The duration of first instability microwave burst monotonically increases from 20 ns to 120 ns in oxygen plasma and from 10 ns to 50 ns in helium plasma with increasing of heating microwave power, being almost insensitive to variations of the magnetic field. These observations can be explained by the fact that the instability growth rate depends on the density and anisotropy of the hot electrons, which are greatly increased at low gradients of magnetic field (higher $B_{min}/B_{ECR}$) and high power as discussed in Ref. 6.

## IV. DISCUSSION

The observed precipitation of energetic electrons from the trap and the generation of microwave bursts are inherently related to the excitation of electromagnetic waves due to cyclotron instabilities. The dense (cold and warm) plasma component determines the dispersion relation and damping of propagating waves which can resonantly interact with the energetic electrons. Kinetic cyclotron instabilities are driven by warm and hot electrons with an anisotropic velocity distribution in which the transverse velocity (with respect to the external magnetic field) is considerably higher than the longitudinal velocity. The interaction between the high-frequency waves and resonant electrons leads to diffusion of energetic electrons in the velocity space. These electrons are eventually expelled into the loss cone. The comprehensive study of cyclotron instability in the afterglow of ECR discharge in argon plasma[10] has shown that instability is driven by the resonant interaction of hot electrons with slow extraordinary wave, which propagates quasi-parallel to the magnetic field.

The proposed mechanism explains the main features of the observed microwave emission in the decaying plasma of a minimum-B ECRIS. Temporal characteristics of the instability, such as the delay between heating bower trailing edge and the instability, and the period between pulses, are dictated by the plasma decay rate, which is different in helium and oxygen plasmas. The confinement time is less for oxygen plasma since it has higher average charge and plasma density and lower electron temperature than helium plasma. Moreover, the growth rate of slow extraordinary wave is higher in more dense plasma, that is why the instability appears earlier in oxygen plasma. The research results can be claimed not only to improve the understanding of modern ion sources but also advance studies of wave-particle interactions in non-equilibrium plasma.


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